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多层合采试井分析方法

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摘要：针对多层层间无窜流，原始地层压力不同，各层物理、几何参数不同、无封隔器合采情况下的试井问题，考虑井储与表皮，定义了多层合采试井的无量纲初始井筒压力，从而给出了试井模型样板曲线计算方法和分层参数的拟合方法。试井模型的限制条件如下：各层为均质油藏，内边界是全部射开直井，外边界可以是无限大，一条边界，角度油藏，封闭油藏等任意几何形状。通过计算对其中几个典型情况下的多层油藏压力动态进行了分析。

主题词：多层合采；试井分析；方法；分层流量；初始；井筒压力

1 前 言

对于低产层油藏，为使其能达到工业性油流，往往采用多层合采的方法。对于其它情况多层合采也是降低开发成本的重要手段。但是多层合采却给试井工作带来了困难。要得到各层的参数，最直观的方法是用封隔器，分层进行测试。这种方法的缺点有两个：一是测试周期长，作业难度大，需要将压力计、封隔器准确地从一层移到另一层，压力计损坏的概率大；二是在各层原始压力不同的情况下，不能得到合采时的各层相互作用下的动态参数。所以，需要找到一种针对多层合采时新的试井模型及分析方法。

有关多层合采试井问题的研究是试井理论研究的重要方向。最早是由 Lefkovits 等人对窜流仅发生在井筒（多层合采）的多层油藏井筒压力响应进行了研究。以后的研究大致分为两个阶段：第一个阶段主要针对相同原始压力合采情况[1]；第二阶段的研究包括了不同原始压力的效果，并发展了一些新的试井方法[2]。Papadopulos[3]是第一位对层间不同原始压力及分布问题进行研究的人，他给出了双层均质，无限大蓄水层的精确解。Larson[4]解决初始条件不同的多层合采问题，然而他的工作限定了井筒为常流量，无法处理井储问题。

对于考虑井储及复杂条件下的试井分析问题，Kuchuk[5]发表了任意给定的油层及原始压力不相等的多层合采油藏的井筒压力表达式，条件是给定试井期间及试井前的总流量，只要单层问题在拉氏空间有解，这些单层解就可以组合成多层问题的解。

近年来，多层问题的研究趋向于解决考虑各层不同性质及不同边界条件的问题。

本文提出了一种有效的计算方法，该方法考虑井储及表皮，适合均质，直井的各种边界条件下井筒压力的求解，特别适合对现有软件进行改造。

2 数学方法

对各油层均质，直井任意边界条件，N 层，窜流仅发生在井筒的无量纲压力控制方程可表示为

$$\nabla^2 p_{Dj} + 2\pi \frac{q_{Dj}}{K_j}\delta(r_D - r_{wD})_j = \frac{\omega_j}{K_j}\frac{\partial p_{Dj}}{\partial t_D} \quad j = 1,2,\cdots,N \tag{1}$$

初始条件

$$p_{Dj}(t_D = 0) = p_{Dij} \tag{2}$$

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内边界条件在井筒处

$$p_{\mathrm{D}j}(t_{\mathrm{D}})\big|_{r_{\mathrm{D}}=r_{\mathrm{D}j}} = p_{\mathrm{D}j}(t_{\mathrm{D}}, r_{\mathrm{D}j}) \tag{3}$$

外边界条件任意，另外各流入井筒的流量之和为井筒总流量。

定义如下无量纲参数

$$r_{\mathrm{D}} = \frac{r}{r_{\mathrm{w}}} \tag{4}$$

$$t_{\mathrm{D}} = \frac{\chi_{\mathrm{a}}}{r_{\mathrm{w}}^2} t \tag{5}$$

$$q_{\mathrm{D}} = \frac{q}{q_{\mathrm{t}}} \tag{6}$$

$$p_{\mathrm{D}} = p \bigg/ \frac{q_{\mathrm{t}}}{2\pi h_{\mathrm{t}}(K/\mu)_{\mathrm{a}}} \tag{7}$$

$$C_{\mathrm{Dj}} = C_j / 2\pi h_{\mathrm{t}} (\phi\, C_{\mathrm{t}})_{\mathrm{a}} r_{\mathrm{w}}^2 \tag{8}$$

式中　r 为空间坐标；r_{w} 为井筒半径；q_{D} 为无量纲地层流量；q_t 为地面总流量。

其中

$$(k/\mu)_{\mathrm{a}} = \frac{1}{h_t} \sum (k/\mu)_j h_j \tag{9}$$

$$(\phi\, C_{\mathrm{t}})_{\mathrm{a}} = \frac{1}{h_t} \sum (\phi\, C_{\mathrm{t}})_j h_j \tag{10}$$

扩散系数为　$\chi_{\mathrm{a}} = \dfrac{(k/\mu)_{\mathrm{a}}}{(\phi C_{\mathrm{t}})_{\mathrm{a}}}$，　脚标 a 表示平均。

$$h_{\mathrm{t}} = \sum h_j \tag{11}$$

令流度比为

$$K_j = \frac{(k/\mu)_j h_j}{(k/\mu)_{\mathrm{a}} h_{\mathrm{t}}} \tag{12}$$

储容比

$$\omega_j = \frac{(\phi\, C_{\mathrm{t}})_j\ h_j}{(\phi\, C_{\mathrm{t}})_{\mathrm{a}}\ h_{\mathrm{t}}} \tag{13}$$

应有

$$\sum K_j = 1 \tag{14}$$

$$\sum \omega_j = 1 \tag{15}$$

对上述问题，第 j 层任一点的压力可用 Green 函数表示

$$p_{\mathrm{D}j} = p_{\mathrm{D}ij} + \int_0^{t_{\mathrm{D}}} \frac{q_{\mathrm{D}j}(\tau)}{\omega_j} G_{\mathrm{D}j}(r_{\mathrm{D}}, t_{\mathrm{D}} - \tau)\mathrm{d}\tau \tag{16}$$

式中　$p_{\mathrm{D}j}$是第 j 层的无量纲原始压力；$q_{\mathrm{D}j}$是地层流入井筒的无量纲流量。

求解多层合采问题的主要思想是对式(16)作拉氏变换，这样 $q_{\mathrm{D}j}$便可显示表示，再利用外边界条件就可求得井筒压力的表达式。同样，在拉氏空间也可以考虑表皮和井储的影响。

如果考虑表皮的影响，井筒压力 p_{wD}可表示为

$$p_{\mathrm{wD}} = p_{\mathrm{D}j}(r_{\mathrm{D}} = 1) - q_{\mathrm{D}} S_j / k_j \tag{17}$$

式中　S_j 为第 j 层的表皮因子。

其解的形式为

$$p_{\mathrm{wD}} = p_{\mathrm{D}ij} + q_{\mathrm{Dj}}\, S_j / K_j + \int_0^{t_{\mathrm{D}}} \frac{q_{\mathrm{D}j}(\tau)}{\omega_j} G_{\mathrm{wD}j}(t_{\mathrm{D}} - \tau)\mathrm{d}\tau \tag{18}$$

对式(18)作拉氏变换，并将$\overline{q_{\mathrm{D}j}}$显式表示，有

$$\overline{q_{\mathrm{D}j}} = \left(\overline{p_{\mathrm{wD}}} - \frac{p_{\mathrm{D}ij}}{u} \right) \bigg/ \left(\frac{\overline{G}_{\mathrm{wD}j}}{\omega_j} + \frac{S_j}{K_j} \right) \tag{19}$$

u 为拉氏变量，对式(19)求和，注意外边界条件

$$\sum_{j=1}^{N} \bar{q}_{\mathrm{D}j} = \bar{q}_{\mathrm{wDt}} \tag{20}$$

式中　$\bar{q}_{\mathrm{wDt}}$为无量纲地层流入井筒的总流量。

则

$$\overline{q_{\mathrm{wDt}}} = \sum \left(\overline{p_{\mathrm{wD}}} - \frac{\overline{p_{\mathrm{D}ij}}}{u} \right) \bigg/ \left(\frac{\overline{G}_{\mathrm{wD}j}}{\omega_j} + \frac{S_j}{K_j} \right) \tag{21}$$

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$$\bar{p}_{\mathrm{wD}} = \frac{q_{\mathrm{wDt}} + \sum \frac{p_{\mathrm{D}ij}}{u} \Big/ \left(\frac{\overline{G}_{\mathrm{wD}j}}{\omega_j} + \frac{S_j}{K_j} \right)}{\sum \frac{1}{\frac{\overline{G}_{\mathrm{wD}j}}{\omega_j} + \frac{S_j}{K_j}}} \tag{22}$$

如果考虑井储，由流量关系

$$q_{\mathrm{Dt}} = q_{\mathrm{wDt}} + \sum C_{\mathrm{D}j} \frac{\mathrm{d}p_{\mathrm{wD}j}}{\mathrm{d}t_{\mathrm{D}}} \tag{23}$$

式中　q_{Dt}为总的地面流量；q_{wDt}在式(21)中定义；式(23)中右边第二项为井储流体采出的流量。C_j 定义为$\frac{\Delta V_{\mathrm{w}j}}{\Delta p_{\mathrm{w}j}}$；$\Delta V_{\mathrm{w}j}$为第 j 层井储流体体积变化量；$\Delta p_{\mathrm{w}j}$为井筒压力变化第 j 层流出地层的流量；$q_{\mathrm{D}j}$是与从井储中采出量相关的，井储中与 j 层相关的流体体积为 $\Delta V_{\mathrm{w}j}$，假定仅有单层生产，则

$$q_{\mathrm{Dt}j} = q_{\mathrm{D}j} + C_j \frac{\mathrm{d}p_{\mathrm{wD}j}}{dt_{\mathrm{D}}} \tag{24}$$

假定合采时在井筒中流体混合没有化学反应，对上式求和

$$\sum q_{\mathrm{Dt}j} = \sum q_{\mathrm{D}j} + \sum C_j \frac{\mathrm{d}p_{\mathrm{wD}j}}{\mathrm{d}t_{\mathrm{D}}} \tag{25}$$

对式(25)作拉氏变换

$$\bar{q}_{\mathrm{Dt}} = \bar{q}_{\mathrm{wDt}} + \sum C_{\mathrm{D}j} (u\bar{p}_{\mathrm{wD}j} - p_{\mathrm{wD}j}|_{t_{\mathrm{D}}=0}) \tag{26}$$

令总井储

$$C_{\mathrm{t_D}} = \sum D_{\mathrm{D}j} \tag{27}$$

初始井筒压力

$$\tilde{p}_{\mathrm{wD}bij} = \sum \frac{C_j}{C_{\mathrm{t}}} p_{\mathrm{wD}ij} \tag{28}$$

井筒中不考虑重力作用

$$p_{\mathrm{wD}j} = p_{\mathrm{wD}} \tag{29}$$

式(26)可进一步写作

$$\bar{q}_{\mathrm{Dt}} = \bar{q}_{\mathrm{wDt}} + uC_{\mathrm{tD}} (\bar{p}_{\mathrm{wD}j} - \tilde{p}_{\mathrm{wD}bij}/u) \tag{30}$$

利用式(23)得

$$\bar{p}_{\mathrm{wD}} = \frac{\bar{q}_{\mathrm{Dt}} + C_{\mathrm{t_D}} \tilde{p}_{\mathrm{wD}bij} + \sum \frac{p_{\mathrm{D}ij}}{u} \Big/ \left(\frac{\overline{G}_{\mathrm{wD}j}}{\omega_j} + \frac{S_j}{K_j} \right)}{u + \sum 1 \Big/ \left(\frac{\overline{G}_{\mathrm{wD}j}}{\omega_j} + \frac{S_j}{K_j} \right)} \tag{31}$$

上式是考虑了井储和表皮的多层合采井筒压力表达式，将其代入式(21)就可以进行分层流量的计算。

3　样板曲线的计算

对式(31)进行拉氏数值反演，考虑定产量情形，则$\overline{q_{\mathrm{Dt}}} = \frac{1}{u}$。Green 函数根据地层情况选择，如果拉氏空间存在解析解，如无限大地层、一条定压或封闭边界、圆形地层，可直接采用拉氏空间下的 Green 函数进行计算。如果拉氏空间下不存在解析解，如河道状地层、角度边界、U 形地层、盒状地层，可首先将其 Green 函数用拉氏数值正演变到拉氏空间。

4　压力及压力导数曲线特征

计算一组样板曲线的输入参数是 $C_{\mathrm{D}j}$，S_j，ω_j，K_j，$p_{\mathrm{D}ij}$，输出 $\ln(\tilde{p}_{\mathrm{wD}bij} - p_{\mathrm{wD}})$ 对 $\ln(t_{\mathrm{D}}/C_{\mathrm{tD}})$ 和 $\mathrm{dln}(\tilde{p}_{\mathrm{wD}bij} - p_{\mathrm{wD}})/\mathrm{dln}(t_{\mathrm{D}}/C_{\mathrm{tD}})$ 曲线。考察各层不同的储容比 ω_j 流度比 K_j 及原始压力对压力及导数曲线的影响。

4.1　几何形状的影响

图1是多层油藏的 $\ln(\tilde{p}_{\mathrm{wD}bij} - p_{\mathrm{wD}})$ 对 $\ln(t_{\mathrm{D}}/C_{\mathrm{tD}})$ 和 $\mathrm{dln}(\tilde{p}_{\mathrm{wD}bij} - p_{\mathrm{wD}})/\mathrm{dln}(t_{\mathrm{D}}/C_{\mathrm{tD}})$ 曲线。其中，压力(1)～压力

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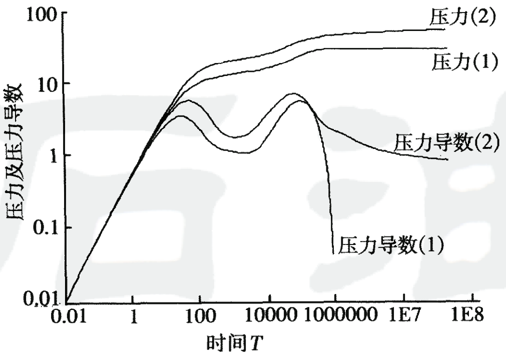

图1　多层合采试井样板曲线

Fig. 1　Well testing type-curve in multi-layered commingled system

导数(1)曲线是两层地层，参数为 $R/r_w=1000$，$C_D=200$，$S_1=S_2=0$，其中一个封闭，一个定压，而且原始压力相同。从图中可以看出到达边界后，受封闭边界影响，压力导数上升，当封闭地层产量趋于0时，定压边界的影响使导数迅速趋于0。图2是对应的分层产量曲线。可以清楚看出分层产量随时间的变化，到边界后定压油藏产量逐渐趋于总产量，封闭地层产量逐渐趋于0。

图1中压力(2)～压力导数(2)曲线是较为复杂的地层情况，地层为三层，地层参数为 $\omega_j=1/3$，$S_j=0$，$C_{Dj}=200$，其中一层为无限大地层，一层为定压地层(边界在 $L_1/r_w=10000$处)，一层为圆形封闭(边界在 $R/r_w=1000$处)，原始压力相同。从图中可以看出，在边界1000处，封闭边界影响使压力导数升高，定压边界和无限大地层同时起作用，使压力导数逐渐降低，逐渐趋于0。图3中分层的产量变化曲线能更清楚边界了解对产量的影响。

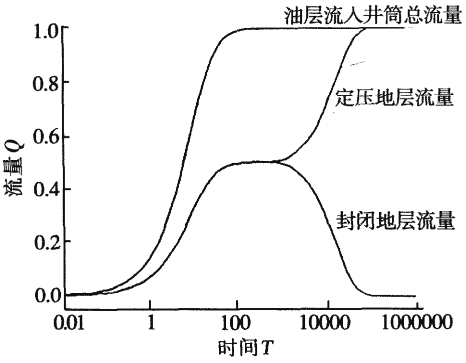

图2　两层合采分层流量图

Fig. 2　Layered-flow rate in two-layered system

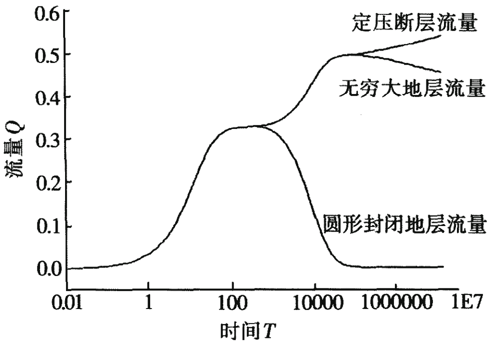

图3　三层合采分层流量图

Fig. 3　Layered-flow rate in three-layered system

4.2　不同原始压力的影响

图4是较为简单情况下两层无限大地层不同原始压力的产量曲线，从中可以看出在初始时，压力低的地层的产量是负的，因为井筒压力比地层压力高，所以被倒灌，然后产量逐渐上升，两层的产量逐渐接近。其压力与压力导数曲线形状与单层无限大地层的类似，由于没有边界，压力和压力导数曲线是分不出层与层之间的区别的。不同之处在于它们的无量纲压力定义不同，最后压力导数趋向的数值有所不同，分别为0.5与1.0。

图5是较为复杂情况下三层地层不同原始压力的产量曲线。三层的地层参数分别为：第一层圆形封闭(在

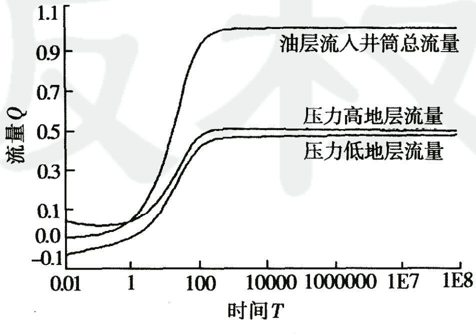

图4　两层不同原始压力分层流量图

Fig. 4　Layered-flow rate with different initial pressure in two-layered system

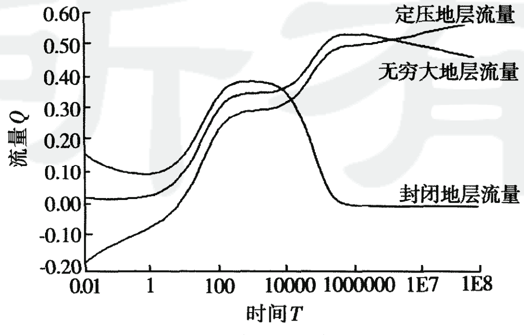

图5　三层不同原始压力分层流量图

Fig. 5　Layered-flow rate with different initial pressure in three-layered system

$R/r_w=1000$处)，压力最高；第二层是无限大地层，压力次高；第三层是定压地层(在$L/r_w=10000$处)，其他参数相等。其压力及压力导数曲线和图1(2)曲线很相似。从产量曲线中可以很清晰地看出，原始压力的不同和边界的影响。

4.3　储容比和流度比的影响

图6是两层定压边界不同储容比情况下的曲线，储容比分别为0.1和0.9。从图中可以看到，当边界影响产生后，两层的产量之比迅速趋于1/9，可见储容比对产量的影响。

两层定压边界不同流度比情况下的曲线与图6类似，流度比分别为0.1和0.9。当边界影响产生后，两层的产量之比也迅速趋于1/9，所以流度比越大，分层产量比越高。

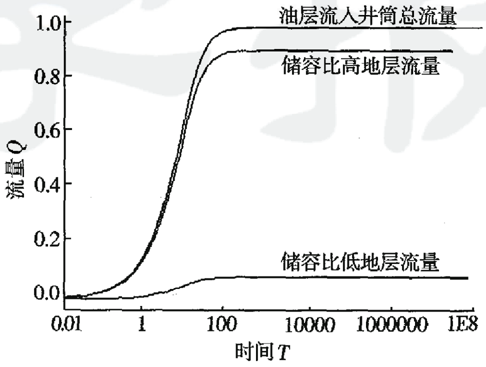

图6　不同储容比对分层流量的影响

Fig. 6　Influence to layered-flow rate with different storage ratio

5　拟合方法

通过计算可以看出，各油层的几何参数，原始压力对井筒压力及其导数影响较大，而储容比，流度比对井筒压力及其导数影响较小，因此拟合参数选择油层几何参数，井储及表皮，考虑到原始油层压力可以通过其它地层测试方法准确地得到，可将它与储容比及流度比作为已知参数输入。所以，最终通过样板曲线拟合的输出结果是：(1) 各油层几何参数；(2) 通过压力拟合值确定平均流度$(k/\mu)_a$[参见式(5)]；(3)通过时间拟合值确定总井储C_t[参见式(6)]；(4) 通过$C_{tD}e^{2s}$确定总表皮S。

值得一提的是，所有这些参数对各层流量随时间的变化都有很大的影响。如果能在试井的同时进行各层分流量的测试，在进行压力拟合的同时，也进行分流量拟合将会给多层合采试井分析提供更加准确可靠的拟合结果。但是这种方法还需要测试技术进一步发展。

6　结　论

1. 提出多层均质直井，任意边界条件，窜流仅发生在井筒的多层合采试井井底压力的计算方法，其中无量纲定义，图版坐标的选取是新颖的，该方法便于对现有的软件进行改造。

2. 通过大量的计算，筛选出对压力变化影响较大的参数，如油层几何参数、井储及表皮作为拟合参数，其他参数储容比、流度比作为已知量输入。

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rocks exist.

Key words: Jungar Basin;petroleum origins;oil components;oil-bearing fluid inclusions;reservoirs

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HIGH-RESOLUTION SEQUENCE STRATIGRAPHICAL RESEARCH IN RESERVOIR DEVELOPMENT STAGE OF WENMI OILFIELD **ACTA** 1999,20(5):33~38.

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Taking the oil-bearing series of Wenmi Oilfield in Turpan-Hami Basin as an example,this paper has studied the techniques and methods for high-resolution sequence stratigraphical research within reservoir in terrestrial oilfield in development stage. A new method was proposed that recognition and correlation of flooding surfaces and chronostratigraphic units through the integration of cores,well-logging and well-logging constrained seismic inversion data. Through the comprehensive analysis of formation relation,natural gamma ray logging data,gamma ray spectrometric data,petrology and x ray diffraction,the origin and sequence stratigraphic significance of the low-gamma shale were studied. The results show that the low-gamma shale was deposited in the lake-flooding stage which inhibited the deposition of minerals with high radioactivity such as k-feldspar and mica,so the low gamma shale may be referred as the recognition marker of flooding surfaces. The correlation of flooding surfaces and high resolution chronostratigraphic units can be made using well-logging constrained seismic inversion data. Based on this,a high resolution chronostratigraphic framework of oil-bearing series of the Sanjianfang formation in Wenmi Oilfield was built,which provides the basis of research of reservoir flow units and percolation barriers.

Key words: high-resolution; sequence stratigraphy; natural gamma ray logging; well-logging constrained seismic inversion; Wenmi Oilfield;Jurassic;reservoir development

A METHOD TO DESCRIBE RESERVOIR HETEROGENEITY **ACTA** 1999,20(5):39~42.

Zhao Chunsen et al. (*Daqing Petroleum Institute*)

Quantitative reservoir description is essential to reservoir development,especially for an EOR project. Only using static information such as logging and core to build up a reservoir model can't reflect the flow characteristic of fluid in a porous medium efficiently. As everyone knows,methods of pulse test and numerical simulation have played an important role in reservoir behavior analysis. In this paper,the two methods are combined to determine the permeability distributions of each layer in a heterogeneous reservoir by matching the interference tests and supposing that the reservoir consists of many layers which with different effective thickness,permeability and fluid saturation distributions. The polymer flooding pilot in Daqing showed the practical application and satisfactory results.

Key words: reservoir description; pulse test; geologic model; numerical simulation; heterogeneity; quantitative description

A METHOD OF PRESSURE ANALYZING FOR MULTI-LAYERED COMMINGLED RESERVOIR **ACTA** 1999,20(5):43~47.

Xu Xianzhi et al. (*University of Science and Technology of China*)

In this paper,the problem is studied about the well test of analyzing a multi-layered commingled reservoir with unequal initial layer pressure,unequal physical parameter,unequal geometric parameter,and none flow between the layers. In the case of commingled production,the well bore storage and skin effect are considered. The computing method of typical curve of well test model and the matching method of the parameters of each layer are given as well. The defined condition of well test model is that each layer is homogeneous reservoir,inner boundary is penetrated straight well,outer boundary may be infinity,semi-infinity,angle reservoir,closed reservoir. Transient pressure analysis is performed through the calculation of some normal boundary condition.

Key words: multi-layered commingled reservoir;analysis of well test;method;layered-flow rate; initial wellbore pressure

石油学报

MATHEMATICAL SIMULATION OF TWO-PHASE PERCOLATION IN THE DIRECTION OF NORMAL OF ELLIPSE AND CALCULATION OF DEVELOPMENT INDEXES **ACTA** 1999,20(5):48～53.

Deng Yinger et al. (*Institute of Porous Flow and Fluid Mechanics,Chinese Academy of Sciences*)

Hydraulic parting,which can form a symmetrical and vertical plane of fracture in the formation that surrounds a well is an effective measure of increasing production. A vertical fractured well can bring out two-dimensional flow in the direction of normals of developing ellipse-conjugate equal-pressure ellipse and hyperbola streamline bunches whose focal points are the two ends of the fracture when it works. A mathematical model of oil and water two-phase fluid flow in the normal direction of the ellipses, which is a nonlinear equation with a moving boundary is established according to concepts of turbulent ellipses and equivalent developing regulations. Characteristic solution and finite difference solution to the model are derived respectively and water saturation distribution curves are presented. And the variation of regularity moving boundary is found. Results showed good agreement between the characteristic solution and finite difference solution. Moreover,formula of water-flooding development indexes for vertical fractured wells are derived. Laws of change of production and pressure difference with time are recognized. The paper provides numerical simulation, dynamic analysis and prediction of water-flooding development of oilfields in the case of vertical fractured wells with theoretical basis.

Key words: vertical fractured well;two-phase fluid;moving boundary;nonlinear equation;finite difference method;development index

ENHANCING OIL RECOVERY BY MICROBIAL PROFILE CONTROL **ACTA** 1999,20(5):54～57.

Gao Xuezhong et al. (*Tianjin Industrial Microbiology Institute*)

The paper discussed a method of enhancing oil recovery by water injection profile control with microbe and its metabolize products in oil reservoirs. It has advantages over the routine (mechanical and chemical) profile control methods in many aspects. A group of microbe with saltresisting and temperature-adapting of 30～60℃ were separated,which can live compatibly with the original microbe in reservoir and can plug the core whose permeability is less than $20\mu m^2$ with the plugging ratio more than 90%. It includes coccus,bacilli and mycelia. The paper also described the microbe characteristics and the mechanism of microbial profile control. It is proved that the microbe separated can effectively reduce the core permeability in lab simulation profile control test and improve the oil recovery in field test.

Key words: oil production;microbe;profile control;EOR;permeability

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PETROLEUM ENGINEERING

SIMULATION STUDY OF INTERACTION BETWEEN OUTER TEETH AND THE WALL OF BOREHOLE **ACTA** 1999,20(5):58～61.

Wu Zebing et al. (*Southwest Petroleum Institute*)

Teeth (including gage insert,trimmer and off-gage insert) in the heel area play an important role in the drilling operation. They can improve both the rate of penetration (ROP) and the quality of the borehole wall. Based on modern geometry of roller cone bit,spatial models of a cone bit and transitory area of wall,the discrete model of a tooth,the model of bit/rock interaction are established. According to the above models,the corresponding simulation software are developed. The cutting ability of teeth in the heel area are evaluated and analyzed by the software. The process of interaction between bit and rock can be shown on the screen. At the same time,cutting work,frictional work and volume of rock cut can also be obtained. The software can guide designers to arrange teeth on cones correctly,which has a significant meaning in improving the whole performance of a cone bit.